UNIVERSITY OF LEEDS

Numerical Simulations of Dusty Colliding Wind Binaries

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Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

August, 2021

This thesis is dedicated to my Mum, without her help these past 26 years, there's no way I would have written this.

I'll pay you back I promise!

Acknowledgements

No good thesis[1] wouldn't be complete without a commitment to the authors friends. I first met some of you on literal day one of my undergraduate degree in Leeds, it's really quite incredible how you've all tolerated my nonsense for so long. From essentially forcing my way into Rob's house so I could cook some disastrous fried chicken, to playing Super Smash Bros. all night long on it's release day, to watching trashy movies over the internet at the height of the pandemic, these are moments I'll treasure for the rest of my life. Thank you all, for making me so happy these last 9 years. In particular, those who are still in Leeds, Rob, Matt, Kelsie and Alex; as well as those who aren't, Martin, Caz, Andy, and Devon.

To my partner Pruthvi, I cannot stress how unlikely it is that the two of us even met; two people finding each other on esoteric circles of the internet is like two particles colliding in the tenuous interstellar medium, if you'll excuse the extremely trashy metaphor. You've been supportive, helpful, and the most wonderful partner anyone could ask for; I truly am blessed to know you and love you.

I would also like to thank the wonderful team at Leeds' ARC High Performance Computing department, considering the bulk of this work involves many 3D numerical simulations my use of ARC 4's compute nodes can be described as somewhere from "excessive" to "taking the piss". I also apologise for running my earlier simulations on the login nodes for multiple days, I swear it was an accident.

Finally, I would like to thank Leandro Panizzon and his wife, Margarita, though Methylphenidate was originally synthesised by him to treat her low blood pressure, it also works quite well for dragging my attention-deficit riddled brain through this PhD.

[1] Though the quality of this one is debatable.

Abstract

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Abbreviations

BODMAS	Binary Orbit Dust Model with Accretion and Sputtering	Section 3.6
CWB	Colliding Wind Binary	Section 2.1.1
GMC	Giant Molecular Cloud	Section 2.1.1
LBV	Luminous Blue Variable	Section 2.1.1
OB	O or B type star	Section 2.1.1
RSG	Red Supergiant	Section 2.1.1
WC	WR Carbon Phase	Section 2.1.2
WCd	Dust forming WC star	Section 2.4.3
WCR	Wind Collision Region	Section 2.4.1
WN	WR Nitrogen Phase	Section 2.1.2
WO	WR Oxygen Phase	Section 2.1.2
WR	Wolf-Rayet	Section 2.1.2

List of common abbreviations, if an abbreviation is important enough to warrant a section in this thesis, the section will be referenced.

Common Symbols

a	Grain radius	
C	Courant-Friedrichs-Lewy condition	
L_*	Stellar luminosity	
M_*	Stellar mass	
$\dot{M}$	Mass loss rate	
v_∞	Wind terminal velocity	
z	Dust-to-gas mass ratio	
η	Wind momentum ratio	
$\Lambda(T)$	Cooling function	
ξ	Grain sticking efficiency	
θ_c	WCR conic approximation opening angle	Equation 2.7
τ_{KH}	Kelvin-Helmholtz timescale	Equation 2.1a
τ_{ff}	Free-fall timescale	Equation 2.1b
τ_{cool}	Cooling timescale	Equation 2.8a
τ_{esc}	Escape timescale	Equation 2.8b
χ	Cooling parameter	Equation 2.9
$\mathrm{M}_\odot$	Solar mass	1.988×10^{33} g
$\mathrm{M}_\odot\,\mathrm{yr}^{-1}$	Solar mass per year	6.301×10^{25} $\mathrm{g\,s^{-1}}$
$\mathrm{L}_\odot$	Solar Luminosity	3.828×10^{33} $\mathrm{erg\,s^{-1}}$
AU	Astronomical Unit	1.496×10^{13} cm
pc	Parsec	3.086×10^{18} cm

List of common symbols, if symbol requires a derivation, the appropriate equation within this thesis will be referenced. If the symbol is a unit, the value in CGS units will be provided instead.

Chapter 1

Introduction and Motivation

Chapter 2

Background

2.1 Early-Type Stars

The term Early-type stars is quite possibly the epitome of Astrophysical naming conventions, it's a very old term, coming from the dawn of astrophysics itself, quite opaque as to what it means, and also by definition *completely wrong*. In fact it is one of the most wrong pieces of terminology I can think of.[1] The first generation of astrophysicists found themselves asking very important questions such as "what even *are* stars" and "what possible mechanism can allow a star to burn for so long?" Each of these questions was rather pressing for the burgeoning field, and the scientific community was aching for an answer.

Of course, like all pressing questions of the 19$^{\text{th}}$ century, it fell to Lord Kelvin to provide a convincing but incorrect answer. Kelvin assumed that gravitational collapse was the mechanism for a stars long-term heating, with younger, "early" type stars shining the brightest. Not only was the mechanism incorrect, but typically older main sequence stars are more luminous than their younger counterparts of a similar mass! However, as is the case with astrophysical terminology, the term stuck, to the confusion of many young astrophysicists.

Instead, we now know that stars produce their energy through fusion. These reactions vary from substellar deuterium and lithium burning, to main sequence p-p & CNO hydrogen burning processes, and finally to the triple-α and other exotic fusion processes for evolved massive stars. The more massive the star the greater the internal pressure, allowing for more exotic fusion processes. The bigger a star, the greater the core pressure and temperature, as all fusion reactions are highly dependent on temperature, stars with only a few dozen solar masses are thousands of times more luminous than our sun, but only live a fraction of the time (Carroll & Ostlie, 2014).

2.1.1 OB-type stars

And with that we shift our gaze to high-mass stars, with the most massive of all being the O and B type stars, these are extremely luminous ($\sim 10^4\,\mathrm{L}_\odot$), and relatively short lived ($\sim 10\,\mathrm{Myr}$) stars. The age-old adage of a candle burning twice as bright lasting

[1] Aside from astrophysicists calling something "warm", of course. That can quite literally mean anything from 10 to 10,000 Kelvin, depending on who you ask, what they're writing about, or how they're feeling at that particular moment. In fact, I'll probably end up falling into this same trap somewhere in this thesis as well!

half as long applies to our studies of the cosmos, but it is more apt to compare a candle and a stick of dynamite when considering stars on opposing ends of the Harvard classification system.

The most common formation mechanism of stars is through the collapse of a giant molecular cloud[1], an enormous cool cloud many parsecs across with a mass of around $10^4 M_\odot$. As this GMC collapses and radiates energy, lowering the radius of thermostatic equilibrium for the cloud, as collapsing progresses the cloud fragments into many smaller regions with a critical density, capable of collapsing further, forming a star. The collapse of a GMC can be described with a series of timescale. First, the Kelvin-Helmholtz timescale, τ_{KH}, which describes the timescale required for the radiating cloud to collapse. The second important timescale is the free-fall timescale, τ_{ff}, which is the time taken for a cloud to collapse. These timescales are described by the following equations:

$$\tau_{KH} \approx \frac{GM_*^2}{R_* L_*}, \tag{2.1a}$$

$$\tau_{ff} = \sqrt{\frac{3\pi}{32G\bar{\rho}}}, \tag{2.1b}$$

where M_* is the protostellar mass, R_* is the protostellar radius, L_* is the protostellar luminosity, and ρ is the mean density of the collapsing cloud (Ward-Thompson & Whitworth, 2011).

Perhaps the most important distinction between massive star formation and its better understood counterpart is as a young protostar approaches the main sequence, the KH timescale is less than the free-fall timescale, meaning the material at the center of the collapsing cloud begins fusion while the bulk of core has collapsed onto the site of the future star. This burgeoning star begins to drive the weakly gravitationally coupled collapsing material away due to its sheer luminosity, driving this material outwards, causing it to accrete and shock material within the GMC.

Another important consideration is the role of angular momentum as the star collapses. The particularly massive cloud involved in massive star formation is more prone to fragmentation, meaning that massive stars typically form with an orbital partner, whilst approximately $2/3^{\text{rds}}$ of low-mass stars are part of a binary or multiple system,

[1] GMC

this value is near-total. As such, the environment within an OB association after star formation consists of numerous young stars in tightly-knit groups disrupting the entire local area.[1]

Above a stellar mass of $1.3M_\odot$ pressures and temperatures within a stellar core favour the fusion of hydrogen into helium through the catalytic CNO cycle, instead of the more direct p-p fusion process.

$$
\begin{aligned}
{}^{12}_{6}C + {}^{1}_{1}H &\rightarrow {}^{13}_{7}N + \gamma \\
{}^{13}_{7}N &\rightarrow {}^{13}_{6}C + e^{+} + \nu_e \\
{}^{13}_{6}C + {}^{1}_{1}H &\rightarrow {}^{14}_{7}N + \gamma \\
{}^{14}_{7}N + {}^{1}_{1}H &\rightarrow {}^{15}_{8}O + \gamma \\
{}^{15}_{8}O &\rightarrow {}^{15}_{7}N + e^{+} + \nu_e \\
{}^{15}_{7}N + {}^{1}_{1}H &\rightarrow {}^{12}_{6}C + {}^{4}_{2}He
\end{aligned}
$$

The reaction rate of CNO rises much faster, resulting in a convective core, surrounded by a radiative envelope (Salaris & Cassisi, 2005). This is the driving force behind the incredible luminosities of an OB star as it hurtles along the main sequence.

Unfortunately for massive stars, pesky fundamental laws such as the conservation of energy come into play. With only an order of magnitude or two of additional mass more than our sun and shining 10^4 times as brightly, this curtails the life of the brightest stars to lifespans not much more than 10^7 years. If we define a galactic year as the time it takes for a star to orbit the Milky Way, these poor stars don't even make it to their first birthdays, which is quite sad really.[2]

As the available hydrogen begins to become depleted, the lowering reaction rates force the star to shrink, this raises the internal temperature until the core begins to burn helium through the triple-α process:

$$
\begin{aligned}
{}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} &\rightarrow {}^{8}_{4}\mathrm{Be} \\
{}^{8}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} &\rightarrow {}^{12}_{6}\mathrm{C} + 2\gamma
\end{aligned}
$$

[1] This is a bit like living in Headingley, Hyde Park, or any other area with lots of Undergraduates.

[2] Continuing this analogy our sun can drink, might have voted if they felt like it, and may be racking up vast quantities of student debt.

The sudden spike in energy radiating from the core shifts the calculus of hydrostatic equilibrium in the favour of outward forces, causing the star to rapidly expand in the form of a Red Supergiant or Luminous Blue Variable (Ryan & Norton, 2010). During this phase the energy output of the star is even greater, with a timescale of $\sim 10^6$ years, this is only temporarily prolonging the life of the star, which will inevitably begin burning heavier and heavier elements, faster and faster. Once the star starts producing iron its fate is sealed, the star stops fusing, and collapses, annihilating itself in the form of a supernova and leaving behind a remnant of its core in the form of a neutron star or black hole (Ward-Thompson & Whitworth, 2011).

Whilst the stars end is as inevitable as it is violent, the intermediate stage as the star leaves the main sequence is in itself extremely interesting, and for the context of this thesis, no product of this stage is more interesting than the Wolf-Rayet.

2.1.2 Wolf-Rayet stars

As we now know, Wolf-Rayets[1] are evolved forms of O-type stars, and are a short lived component of the life-cycle of massive stars, typically lasting for around 5×10^5 years (Crowther, 2007). Despite this relatively transient length of this stage, the influence of a WR star on its local medium is extremely outsized. WR stars in particular are known for having dense, fast winds, typically between 2 and 3 orders of magnitude than their main sequence O-type progenitors, with mass loss rates on the order of $10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ and wind velocities of $1.5 \times 10^3\,\mathrm{km\,s^{-1}}$. This extremely dense wind is driven by the highly energetic helium burning core, which is luminous enough as to drive away the outer layers of the stars envelope, exposing the core. The observed spectroscopic lines are due to heating of the envelope from the core, which is enriched with by-products of hydrogen and helium burning, the lack of hydrogen lines is due to the stars evolved nature, as all the hydrogen has been burned, there is simply nothing left to observe!

Wolf-Rayet stars can be subcategorised through spectroscopic observation, which indicates enrichment in a particular element, the 3 major sub-types, WN, WC and WO are defined by their strong nitrogen, carbon and oxygen lines respectively. The important distinction between WN and WC/WO stars is that WN stars are enriched through hydrogen burning, whilst WC and WO are enriched through the by-products of helium burning (Vink, 2015).

[1]Abbreviated to WR.

As a Wolf-Rayet continues to lose its envelope, additional products of fusion processes are dredged up from the centre of the star. In the case of the WN sub-type, the broad nitrogen lines correspond to the outer layer of the envelope, enriched through the CNO process; after this outer envelope is cast off, the remainder of the envelope exhibits carbon and oxygen lines, indicating enrichment from the triple-α process. Finally, the star evolves further and the innermost region of the envelope is revealed, observed as the strong oxygen lines of a WO sub-type (Neugent & Massey, 2019; Oswalt & Barstow, 2013).

As an O-type star transitions to a Wolf-Rayet, it typically undergoes an intermediary LBV or RSG stage as helium burning begins, this is mass dependent, with the various transitional states described by Crowther, 2007:

$$
\begin{aligned}
\mathrm{O} \rightarrow \mathrm{LBV/RSG} \rightarrow \mathrm{WN(H\text{-}poor)} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN\ 1b}, &\quad \text{for } 25\,\mathrm{M}_\odot < \mathrm{M}_{\mathrm{WR}} < 40\,\mathrm{M}_\odot \\
\mathrm{O} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN(H\text{-}poor)} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN\ 1c}, &\quad \text{for } 40\,\mathrm{M}_\odot < \mathrm{M}_{\mathrm{WR}} < 75\,\mathrm{M}_\odot \\
\mathrm{O} \rightarrow \mathrm{WN(H\text{-}rich)} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN(H\text{-}poor)} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN\ 1c}, &\quad \text{for } \mathrm{M}_{\mathrm{WR}} > 75\mathrm{M}_\odot
\end{aligned}
$$

Wolf-Rayet stars are important in the context of this work due to their outsized influence within a WR+OB binary pair. The WR component of a WR+OB binary has an outsized contribution in returning material to the ISM, whilst also dominating the dynamics of the system, with their winds completely overpowering those of their O-type neighbours. In some cases, the dense, fast wind from the WR can collide with the much more tenuous wind from its partner, forming a strong shock, and a variety of fascinating effects. However, I wouldn't want to spoil too much too soon, but you can skip ahead to section 2.4, where this phenomena is covered in more detail.

2.2 Stellar Winds

Stellar winds have already been discussed to some extent in the previous section, however, due to the significance of winds within this body of work, further detailing of winds must be discussed to gain a better understanding of the dynamics of Colliding Wind Binary systems. This section will cover in brief the study of stellar winds, particularly driving mechanisms from low and high mass stars.

2.2.1 Stellar winds in low mass stars

Thomson scattering wind driving

Dust driven winds

2.2.2 Stellar winds in high mass stars

Star	$\dot{M}$ $M_\odot\,yr^{-1}$	v_∞ $km\,s^{-1}$	Mechanism
Sun	10^{-14}	400	Thomson scattering
Red Giant	$10^{-7} - 10^{-9}$	30	Dust driven
Red Supergiant	$10^{-4} - 10^{-6}$	10	Dust driven
OB Star	$10^{-7} - 10^{-8}$	2500	Line driving
Wolf-Rayet	10^{-5}	1500	Line driving

Table 2.1: Comparison of winds from various types of star

2.2.3 The CAK formalism

2.3 Interstellar Dust

2.3.1 The importance of interstellar dust

2.3.2 Interstellar dust in massive star systems

2.4 Colliding Wind Binary Systems

Colliding Wind Binaries[1], in opposition to all known laws of astrophysical nomenclature, is a easy to understand term - it is a binary system where stellar winds from the member stars undergoing collision. Unfortunately, the simplicity of the systems ends here, CWB systems are extremely complex and poorly understood as they are difficult environments to observe or simulate.

[1] Abbreviated to CWBs.

Early observations beyond visual spectrum led to the discovery of many new astrophysical phenomena, one such discovery were extremely bright persistent thermal x-ray sources, with x-ray The first classification and analysis of Colliding Wind Binary systems were independently performed by Prilutskii and Usov, 1976 and Cherepashchuk, 1976, these systems were found to contain a close binary system, consisting of an evolved WR star and an OB counterpart, as their winds collide, a strong shock forms, heating the winds to temperatures in the order of 10^8 K in the immediate post-shock environment, these extreme temperatures and the large quantity of shocked material accounted for the extremely bright thermal x-ray emission. The evidence was further compounded as the variation of the x-ray flux could be attributed to orbital motion of these binary systems.

2.4.1 The Wind Collision Region

The Wind Collision Region[1] is the most violent and turbulent region of a CWB system, a region where strong shocks lead to temperatures in excess of 10^8 K. These strong shocks contain enormous amounts of mechanical energy, in the region of 10^3 $L_\odot$, WCRs are engines capable of producing huge quantities radiation through multiple thermal and non-thermal mechanisms (Eichler & Usov, 1993; Grimaldo et al., 2019). Despite these extreme conditions, these regions are capable of producing amorphous carbon dust grains at a rate on the order 1×10^{-8} $M_\odot\,yr^{-1}$. As these grains are extremely fragile, this is a conundrum that has plagued researchers in this field, as direct observation of the innermost regions of even nearby WCRs is difficult, bordering on impossible, much of the work in this area involves hydrodynamical simulation.

The properties of the WCR can be described by a small number of parameters. The first of such parameters is the wind momentum ratio, η, which describes the available (Usov, 1991).

$$\eta = \frac{\dot{M}_{\rm OB} v_\infty^{\rm OB}}{\dot{M}_{\rm WR} v_\infty^{\rm WR}}, \tag{2.5}$$

This momentum ratio can also be used to estimate the distance of the apex of the WCR to each star, using the following equations:

[1]WCR

$$r_{\mathrm{WR}} = \frac{1}{1+\eta^{1/2}}, \quad r_{\mathrm{OB}} = \frac{\eta^{1/2}}{1+\eta^{1/2}}, \tag{2.6}$$

where r_{WR} is the distance from the WR star to the WCR apex, and r_{OB} is the distance from the OB star to the WCR apex. Work by Eichler and Usov, 1993 goes further to utilise the momentum ratio to approximate the shape of the wind collision region, further out from the apex of the WCR, the region forms an approximately conical shape with an opening angle, θ_c of:

$$\theta_c \simeq 2.1\left(1 - \frac{\eta^{2/5}}{4}\right)\eta^{-1/3}, \quad \text{for } 10^{-4} \leq \eta \leq 1, \tag{2.7}$$

2.4.2 Cooling in the WCR

$$\tau_{\mathrm{cool}} = \frac{k_B T_s}{4 n_w \Lambda(T_s)}, \tag{2.8a}$$

$$\tau_{\mathrm{esc}} = \frac{d_{\mathrm{sep}}}{c_s}, \tag{2.8b}$$

$$\chi = \frac{\tau_{\mathrm{cool}}}{\tau_{\mathrm{esc}}} \approx \frac{v_{\infty,8}^4 d_{\mathrm{sep},12}}{\dot{M}_{-7}}, \tag{2.9}$$

The presence of dust can also accelerate cooling through additional avenues of radiation emission.

As dust grains collide with ionised gas and electrons, this imparts kinetic energy into the grains, heating them and causing them to emit infrared radiation. Assuming that there is a net accretion of ions and electrons onto the dust grains and the gas is optically thin in the infrared regime, energy is effectively removed from the gas. At particularly high temperatures this effect can dominate over high-temperature radiation processes such as bremsstrahlung,

Work by Dwek and Werner, 1981 is used predominantly in this project to simulate cooling.

The heating rate of a dust grain due to collisions

$$\begin{aligned} H_{\mathrm{coll}} = & n\pi a^2 \langle Q(E,q,U)\rangle \\ & \times \langle v(E-qU) f(a,E-qU) f(a,E-qU)\rangle \,\mathrm{erg\,s^{-1}} \end{aligned} \tag{2.10}$$

This can be simplified and expressed in the equation:

$$
\begin{aligned}
H_{\text{coll}} &= \left(\frac{32}{\pi m}\right)^{1/2} n\pi a^2 (k_B T)^{3/2} h(a,T) \\
&= 1.26 \times 10^{-19} \frac{n}{A^{1/2}} a^2(\mu\text{m}) T^{3/2} h(a,T)\,\text{erg}\,\text{s}^{-1}
\end{aligned}
\tag{2.11}
$$

2.4.3 Dust formation in CWB systems

2.4.4 Important WCd systems

2.4.5 Contemporary research in extragalactic low-metallicity WCd systems

Chapter 3

Numerical Simulation

3.1 The Purpose of Numerical Simulations

3.2 The Mathematics of Numerical Simulations

3.3 Computational Hydrodynamics

3.4 The Athena++ Hydrodynamical code

3.5 Simulating CWB systems

3.5.1 Assumptions

3.6 The BODMAS Advected Scalar Dust Model

3.7 Contemporary Dust Models

3.7.1 The Hendrix dust model

Perhaps the most similar contemporary dust model is the model described in Hendrix et al., 2016 - as this model is concerned with simulating the dynamics of dust within a CWB. This is not to say that these models are identical, of course, as the Hendrix model explores how dust spreads throughout the WCR of WR 98a, in order to compare with observational data using radiative transfer code.

To that end, the main differentiating factors between this model and our model are the driving mechanism and dust evolution. In the Hendrix model dust is modelled as a separate fluid

3.7.2 Future dust models

The increased inertia of dust

Chapter 4

A Parameter Space Exploration of Dust Formation within WCd Systems Using an Advected Scalar Dust Model

Chapter 5

Hydrodynamical Simulations of WCd Systems with an Advected Scalar Dust Model

Chapter 6

Final Notes and Conclusion

Appendix A

Astrophysical Shocks

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